N89-28469

# TIME VARIATION OF GALACTIC COSMIC RAYS

Paul Evenson

Bartol Research Institute
University of Delaware
Newark, Delaware 19716

**Abstract.** Time variations in the flux of galactic cosmic rays are the result of changing conditions in the solar wind. Maximum cosmic ray fluxes, which occur when solar activity is at a minimum, are well defined. Reductions from this maximum level are typically systematic and predictable but on occasion are rapid and unexpected. Models relating the flux level at lower energy to that at neutron monitor energy are typically accurate to 20 percent of the total excursion at that energy. Other models, relating flux to observables such as sunspot number, flare frequency, and current sheet tilt are phenomenological but nevertheless can be quite accurate.

**Introduction.** By definition, galactic cosmic rays are charged particles, electrons and nuclei, which occupy the local region of interstellar space. Unlike photons, the charged cosmic rays cannot travel in straight lines through the magnetic fields (typically one microgauss) which permeate the galaxy. Particles of energy less than about 10 GeV, which are the only ones numerous enough to contribute significantly to the radiation background of a spacecraft, have radii of curvature in this field which are small compared to the dimensions of the solar system and tiny compared even to the distance to the nearest star.

Therefore even though these particles have speeds near that of light their convoluted paths in the interstellar medium are such as to completely randomize their directions and smooth out any fluctuations in density. On the timescale of a human lifetime it is inconceivable that there could be any detectable time variation in the fluxes of these particles.

However, as Figure 1 shows, fluxes of galactic particles which penetrate into the solar system exhibit substantial time variations. Particles of different species and/or different energies show obviously related but nevertheless distinctly different variations. It is my aim in this paper to provide a brief and qualitative discussion of the causes of time variability of galactic cosmic radiation. I hope that I cause no offense by choosing not to give references in the text. Instead I present a list of suggestions for further reading chosen in part because they contain extensive references to the literature.

**Solar Modulation.** The variability, or modulation, of the galactic cosmic ray fluxes was recognized some time ago as related to the general eleven year cycle of solar activity, hence the term "Solar Modulation." Figure 1 shows approximately one complete cycle of this activity and illustrates the inverse nature of the relationship. Sunspots, solar flares, and the like were at a maximum during the years 1980-1982 while the fluxes of cosmic rays were at a minimum. A naive explanation, that the extra "stuff" coming off the sun at solar maximum somehow drives the cosmic rays out of the solar system, is very close to the truth. Beyond this point however intuition fails and the details of the process are the subject of much scientific research and debate.

Cosmic ray particle density and the particle density in the solar wind are so low that the particles almost never physically collide with one another. All of the interactions take place through electromagnetic interactions. The electromagnetic fields can be described mathematically in many ways; generally they are described in terms of Fourier components or waves. Because they propagate in an anisotropic, conductive medium, these waves in turn cannot be completely characterized by pointlike measurements from spacecraft. Further, they are almost invisible to remote sensing techniques such as radio sounding although analysis of fluctuations in spacecraft telemetry signals does provide important input into the problem. If a precise, time dependent model of the electromagnetic fields within the heliosphere were available calculation of solar modulation would be only a numerical problem, albeit a complex one, much in the fashion of calculating global weather. In practice, particle observations are often used as the basis for constructing approximate models of the electromagnetic fields.

In order to understand the propagation of cosmic rays in the heliosphere three processes must be considered: diffusion, convection, and adiabatic deceleration. To understand these, consider Figure 2, a highly schematic representation of the heliosphere, or sphere of influence of the sun. The boundary of the heliosphere, which may or may not be sharp, is the surface where the expanding and weakening solar wind can no longer push back the interstellar medium. Because the sun is moving with respect to the interstellar medium it is likely that the boundary is not spherical at all. Estimates of the distance to the boundary have been historically very consistent -- always approximately twice the distance to the furthest spacecraft. Hence, in 1987, most people would place the boundary at approximately 100 AU (one Astronomical Unit is the average earth-sun separation).

Cosmic rays individually have high energies but their total energy content is low compared to the particles which make up the solar wind. Therefore they play little role in the dynamics of the solar wind and are only weakly coupled to the waves created by the lower energy particles. The boundary as such, even if it is sharp, is scarcely seen by the cosmic rays as a barrier; the weakly interacting cosmic rays respond only to the bulk properties of the medium within which they propagate.

Hence the picture of the heliosphere given in Figure 2. The solar wind is seen by the cosmic rays as a collection of radially moving scattering centers that are irregularities and fluctuations in the interplanetary magnetic field. The cosmic rays **diffuse** in this sea of scattering centers, a process which can be characterized by a mean free path, the numerical value of which is typically 0.3 AU at the location of the earth. The process is similar to molecules of perfume diffusing from an open bottle through the air in a room. If the solar wind were not flowing, eventually cosmic rays would diffuse until the intensity throughout the heliosphere became the same as that in interstellar space.

But the solar wind is not stationary, it flows outward at approximately 400 km/second. This flow results in the **convection** of the cosmic rays which are diffusing in the rest frame of the solar wind. One could liken this to aiming a fan at the perfume bottle. This could reduce or even eliminate the scent at some locations depending on the relation of the flow speed to the rate of diffusion.

The wind is expanding as it moves out so cosmic rays trapped in the expansion are in effect cooled much as a gas is cooled by adiabatic expansion against a piston. This process, termed **adiabatic deceleration,** makes modulation complex, as the energy losses are large (hundreds of MeV for a 1 GeV proton) and the flux of particles is strongly energy dependent. The paradoxical nature of this effect can best be seen by noting that at lower energies, where the flux increases with increasing energy, adiabatic deceleration represents a net source of particles at a given energy, rather than a net sink. This idea, that there can be apparent sources of particles deep within the heliosphere must be kept in mind when trying to understand radial gradient measurements.

One final point is worthy of some note. The previous discussion has treated the scattering centers as if they were interplanetary billiard balls scattering cosmic marbles. Such a view is useful to some level, but at a deeper level leads to contradictions which I only mention but do not explore. Under a Galilean transformation a billiard ball is still a billiard ball, so one may treat the scattering in a convenient frame and then transform trivially to another frame moving uniformly with respect to the first. Magnetic fields, even in the non-relativistic limit of a Galilean transformation, do not stay simply as magnetic fields, they change slightly in magnitude and electric fields appear. (That is why dynamos work.) In the solar wind the process is further complicated by the fact that there is no overall rest frame. Because of the expansion, a small volume element of the solar wind is not only expanding itself but its center has a net motion with respect to the centers of other volume elements.

**Magnetic Fields on the Sun.** To understand the magnetic field in the heliosphere it is useful to know a little about the structure of the sun. The energy of the sun is thought to be generated in the central regions, approximately confined to a sphere with a radius one quarter that of the sun (and thus within only about 2% of the volume of the sun). The heat is transported by (radiative) conduction most of the way to the surface. About 85% of the way to the surface the method of heat transport switches to convection. Currents generated by the convective motion in this outer layer of the sun probably support the surface magnetic field. At the surface, the field is highly complex, with regions of positive and negative polarity found in both hemispheres. Only at altitudes of a solar radius or more has the dipole component begun to dominate the field, giving a net polarity to an entire hemisphere. In contrast, the currents producing the earth's field lie deep within the planet, so that at the surface the dipole component is already dominant. Again in contrast to the earth, where changes and reversals of the field take place on timescales of millenia, the magnetic field of the sun reverses its polarity every eleven years, during the period of maximum solar activity. Thus the eleven year solar cycle should more properly be viewed as half of a 22 year cycle. Subtle effects of the 22 year cycle are the subject of intensive study at the present time.

**The Solar Wind.** "Solar Wind" is the name given to the continuous flow of plasma from the sun outward into the heliosphere. The solar wind has its origin in the hot corona, or outer atmosphere of the sun which is so dramatically visible at the time of total eclipses. The hot coronal plasma expands against the force of gravity in a process that has many similarities to the operation of a rocket nozzle. Thermal energy is converted to bulk motion with such high efficiency that the solar wind is highly supersonic. For solar wind protons, the random motion contains only about 10% of the energy of the bulk flow, which has a typical velocity of 400 km/second. The motion of individual solar wind particles is almost purely radial, however it is important to note that the locus of particles which have come from the same area of the sun forms a spiral pattern exactly like that from a garden sprinkler (Figure 3).

**Interplanetary Magnetic Fields.** Even though the solar wind plasma is tenuous (about 1 per $cm^3$ at the orbit of earth) the conductivity is high enough that magnetic fields are "frozen in": their decay or diffusion rate is slow compared to the time it takes the solar wind to reach the heliospheric boundary. The dominant source of the magnetic field is the dipole component of the solar field which threads through the corona where the solar wind is forming. As a result of this process, it can be shown that the field lines in the corona are drawn out into the solar wind and end up following the loci of the particles flowing from one region of the sun. Thus the field forms the familiar Parker spiral shown in Figure 3. Typical field amplitudes at the orbit of earth are a few nanotesla.

Cosmic rays propagate mainly along these field lines. Therefore the picture is not quite so simple as shown in Figure 2; the boundary is much further away along the path the cosmic ray must take. It is of course irregularities in this magnetic field which provide the scattering which results in the diffusion of the cosmic rays. Some of these irregularities are remnants of the irregularity of the solar source of the plasma, but others are undoubtedly generated by various types of plasma processes as the solar wind propagates through the heliosphere.

**Observational Data.** Cosmic ray fluxes vary greatly with energy and particle species. They are also to a good approximation isotropic, in that any detector has a counting rate independent of its direction of view. Flux and energy units in common use are chosen in a way which best exhibits the systematic nature of the energy and composition variability. Particle energies are measured in electron volts (eV), which is the amount of energy required to move a unit electric charge (such as an electron) through a potential of one volt. Cosmic rays are relativistic particles, so it is convenient to refer to the mass in terms of an equivalent energy, a proton therefore has a "mass" of 931 MeV (properly MeV/$c^2$) and an electron 511 keV. It is an observational fact that the relative abundances of cosmic ray nuclei are nearly constant as a function of velocity, which for relativistic nuclei is most commonly described as kinetic energy per unit rest mass. For practical purposes the mass difference between neutrons and proton and that due to nuclear binding energy are insignificant. The mass of a nucleus is therefore conveniently characterized by the number of nucleons (A) and the usual velocity unit becomes kinetic energy per nucleon.

For particles propagating in magnetic fields the best ordering parameter is rigidity (momentum per unit charge). In a magnetic field not changing in time this parameter completely determines the trajectory of the particle; the velocity determines only how fast the particle traverses the trajectory. Momentum, $p$ (in the units MeV/c) is calculated relativistically from kinetic energy, $E$, and rest mass, $m$, by the formula

$$p^2 = E^2 - 2Em$$

Rigidity, expressed in a unit commonly called the volt, but bearing only a distant relationship to the ordinary volt, is the total momentum of the particle divided by the net charge. With the exception of the so called anomalous component cosmic ray nuclei are fully stripped and the net charge is the atomic number Z. For electrons of cosmic ray energies the total energy, kinetic energy, momentum, and rigidity are approximately equal numerically.

Cosmic ray flux is measured as the number of particles striking a unit area per unit time from a unit solid angle. A flat detector of area $s$ cm$^2$ sensitive to particles from one side receives particles from a half sphere, or $2\pi$ steradians. Because of projection effects the net **geometry factor** of such a detector is only $s\pi$ cm$^2$-steradian. At low energies relevant to spacecraft radiation dose the flux of cosmic rays is almost always given as a differential spectrum, a number of particles within a stated interval about the stated energy. Both the energy and the energy differential are often given in terms of energy per nucleon so some care must be taken when using a published spectrum to calculate total dose; extra factors of the number of nucleons can easily be lost.

The most readily available continuous cosmic ray data come from neutron monitors. These ground based detectors are sensitive to the fragments produced by primary cosmic rays as they strike the atmosphere. Cosmic rays must have energies upwards of 1 GeV before the secondaries they produce can strike the ground, therefore the neutron monitors provide information only about the higher energy particles. The earth's magnetic field also screens out cosmic rays. At the equator only particles with rigidities over 20 GV are able to get in, while near the poles the neutron monitor response is limited by the atmosphere.

It is therefore possible in principle to get accurate spectra from 1 GeV to 20 GeV or so for protons (the dominant component) using ground based data. In practice it is difficult to normalize the data properly from one station to the next, therefore such spectra are not readily available. Current research using neutron monitors is done with time variations from individual stations or matched pairs of stations looking for effects at the level of tenths of a percent. Modulation models can be successfully linked to a few selected stations as the behavior of the spectrum is quite regular to the accuracy required to estimate dose. Extrapolation of the neutron monitor data via appropriate models to lower energies is quite successful, although it is possible to have errors as large as a factor of two in flux under certain circumstances.

Below 1 GeV, data on cosmic rays are obtained from spacecraft and sometimes balloons. Normally spectra for protons and helium below 150 MeV/nucleon can be obtained, with an integration time of about ten days, for almost any date desired. The energy range 150MeV/n to 1 GeV/n is poorly monitored on a routine basis, but interpolation between lower energy data and neutron monitors is generally accurate to 20% or better.

**Absolute Level of Modulation.** Although cosmic electrons contribute little to the total dose, and measurements of their flux are sparse, they provide the one direct link to the region outside the heliosphere from which the absolute amount of solar modulation may be calculated. Microwave synchrotron radiation produced by the electrons as they spiral around the interstellar magnetic field can be detected and measured quantitatively by earth based radiotelescopes. These data can in turn be used to estimate the electron flux outside the heliosphere, the so-called Local Interstellar Spectrum or LIS. Figure 4 shows the electron LIS together with an electron spectrum obtained at earth during 1977, a year representative of maximum electron fluxes at earth. Note particularly the large amount of modulation which is present at energies below 1 GeV even at this time of solar minimum. Estimates of modulation model parameters (see below) are made by comparing the model calculation (line through data points) with the data while keeping the input spectrum at the heliospheric boundary constant and equal to that deduced from the radio data.

**Modulation Models.** Transport of cosmic rays through the interplanetary medium is described mathematically by an equation of the Fokker-Planck type which relates the three fundamental processes, diffusion, convection, and adiabatic deceleration discussed above. Obtaining practically useful solutions of this equation remains a difficult task because of the need to deal with spatial anisotropies and inhomogeneities of the interplanetary medium. Even if these effects are included in the mathematical solution, data of sufficient accuracy are not available over enough of the solar system to permit a truly *ab initio* calculation. Solutions are generally obtained by numerical methods, most of which have many free parameters. In practice most of these parameters must be fixed at nominal values and only a few varied to obtain agreement with the data.

Typically the diffusion coefficient as a function of momentum and position and the distance to the boundary are taken as adjustable parameters.

Figure 5 illustrates such a modulation model. In this figure are plotted data and model fits showing the range of variation observed in the spectrum of cosmic ray protons. Modulation measured by the electrons is used to trace back from the observed proton spectrum to the presumed local interstellar spectrum (LIS). Success of the model therefore corresponds to recovering the same LIS during periods of different modulation amplitude. I should note that the LIS in Figures 4-6, including the electron LIS, have been refined over the years to provide the best overall fit to all observations. (Modifications made to the electron LIS are within the quoted error limits of the radio measurements.) One further point to note in Figure 5 is that the high level of solar activity which reduces the cosmic ray fluxes in 1982 compared with 1977 leaves its mark in the form of greatly increased fluxes of low energy particles.

Figure 6, illustrating the modulation of cosmic ray helium, is in many respects similar to Figure 5. The shapes of the LIS are nearly identical when plotted as a function of energy per nucleon (velocity). The overall shape and behavior of the modulated spectra are similar and a component of solar flare helium is clearly visible during 1982. However there are some key points of difference as well. Effects of modulation are smaller on helium at the same energy per nucleon than they are on protons because helium nuclei are more rigid, having twice the charge but four times the mass of the protons. At low energies the so called anomalous component of helium stands out in the 1977 data. Anomalous cosmic rays are most probably singly charged ions produced by sunlight falling on neutral atoms of the interstellar medium which enter the solar system because of the proper motion of the sun with respect to the local gas cloud. These ions are accelerated to high energies by a process which is not well understood. Their anomalous properties with respect to modulation are due to their high rigidity (from their low net charge) and the fact that they are injected deep within the modulation region rather than having to diffuse in from the boundary. (Before the particles are ionized they do not interact significantly with the solar wind and propagate freely through the magnetic fields.)

**Model Weaknesses.** Often attempts are made to construct models relating cosmic ray flux to observables such as sunspot number, flare frequency, and current sheet tilt. All of these are correlated with each other in some general way so the models do a good job with general trends but in detail tend to predict the past much better than they predict the future. Current models of modulation do provide a systematic basis for calculating fluxes and spectra of many particles based on a few direct cosmic ray observations.

To date it has been observed that maximum cosmic ray fluxes, which occur when solar activity is at a minimum, are well defined and reproducible from one solar cycle to the next. Reductions from this maximum level are typically systematic, slow and predictable in a general sense but on occasion are rapid and unexpected. Most rapid fluctuations are reductions in flux (Forbush decreases) so conservative calculations can be based on the nominal model. Of course the real danger of an upward fluctuation comes from solar flare particles which are not considered in this paper.

Models that do a good job of ordering observations at one location seldom permit accurate extrapolations to flux levels elsewhere in the solar system. This may be due to fundamental problems with the physics of the models. Small differences in the behavior of positive and negative particles may be a symptom of large scale particle drifts, possibly associated with the magnetic neutral sheet separating the regions of opposite magnetic polarity. On the other hand, the models may be sound but the model parameters may vary with radial distance and distance from the ecliptic in ways which are not currently understood.

**Summary.** Current modulation models are quite good at reproducing the relative modulation amplitudes near the earth of most of the cosmic rays. By using a few key indicators, such as neutron monitor measurements and low energy proton data, flux levels of other components can be calculated to an accuracy of 20%. These calculations unfortunately do not usually give good predictions of the flux at other locations in the heliosphere.

**Acknowledgements.** This paper is based on a talk given at the Workshop on the Interplanetary Charged Particle Environment, held at JPL on March 16 and 17, 1987. I would like to thank John Simpson, Peter Meyer, Roger Pyle, and Moises Garcia-Munoz for their assistance in supplying data and model fits for the figures, and Leo Krawczyk for technical assistance in preparing the figures. Preparation of this paper was supported in part by NASA Grant NAG-5-374 and NSF Grant ATM86-03192.

**Bibliography.** The following are suggested to the reader who would like a more detailed and technical treatment of the process of solar modulation. This list is not intended to be exhaustive in itself, however the publications cited contain within them references to most of the significant literature on the subject.

Bieber, J. W., P. Evenson, and W. H. Matthaeus, Magnetic helicity of the IMF and the solar modulation of cosmic rays, *Geophys. Res. Lett., 14,* 864-867, 1987.

Evenson, P., M. Garcia-Munoz, P. Meyer, K. R. Pyle, and J. A. Simpson, A quantitative test of solar modulation theory: The proton, helium and electron spectra from 1965 through 1979, *Astrophys. J. Lett., 275* L15, 1983.

Fisk, L. A., Solar modulation of galactic cosmic rays, 2, *J. Geophys. Res., 80,* 1701, 1971.

Garcia-Munoz, M., P. Meyer, K. R. Pyle, J. A. Simpson, and P. Evenson, The dependence of solar modulation on the sign of the cosmic ray particle charge, *J. Geophys. Res., 91,* 2858-2866, 1986.

Jokipii, J. R., Cosmic ray propagation I: Charged particles in a random magnetic field, *Astrophys. J., 146,* 480-487, 1966.

Jokipii, J. R., E. H. Levy, and W. B. Hubbard, Effects of particle drift on cosmic ray transport I: General properties, application to solar modulation, *Astrophys. J., 213,* 861-868, 1977.

Mc Kibben, R. B., Galactic Cosmic Rays and Anomalous Components in the Heliosphere, *Reviews of Geophysics, 25,* 711-722, 1987.

Parker, E.N., *Interplanetary Dynamical Processes,* New York: Interscience, 1963

Shea, M. A., Solar-Planetary Relationships: Cosmic Rays, Solar and Interplanetary Physics, *Reviews of Geophysics, 25,* 641-650, 1987.

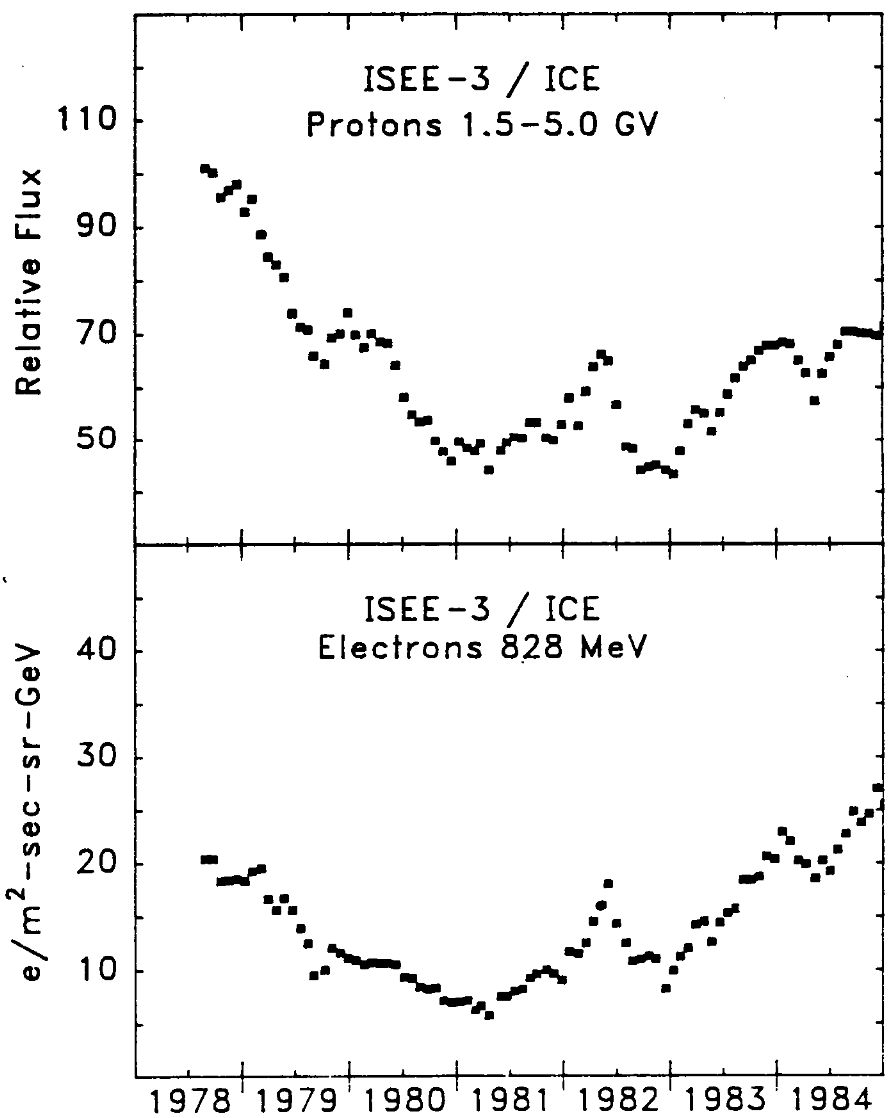



*Figure 1.* Time variability of galactic cosmic ray proton and electron fluxes. Overall similarity is apparent but close observation shows differences which depend on energy and charge sign.

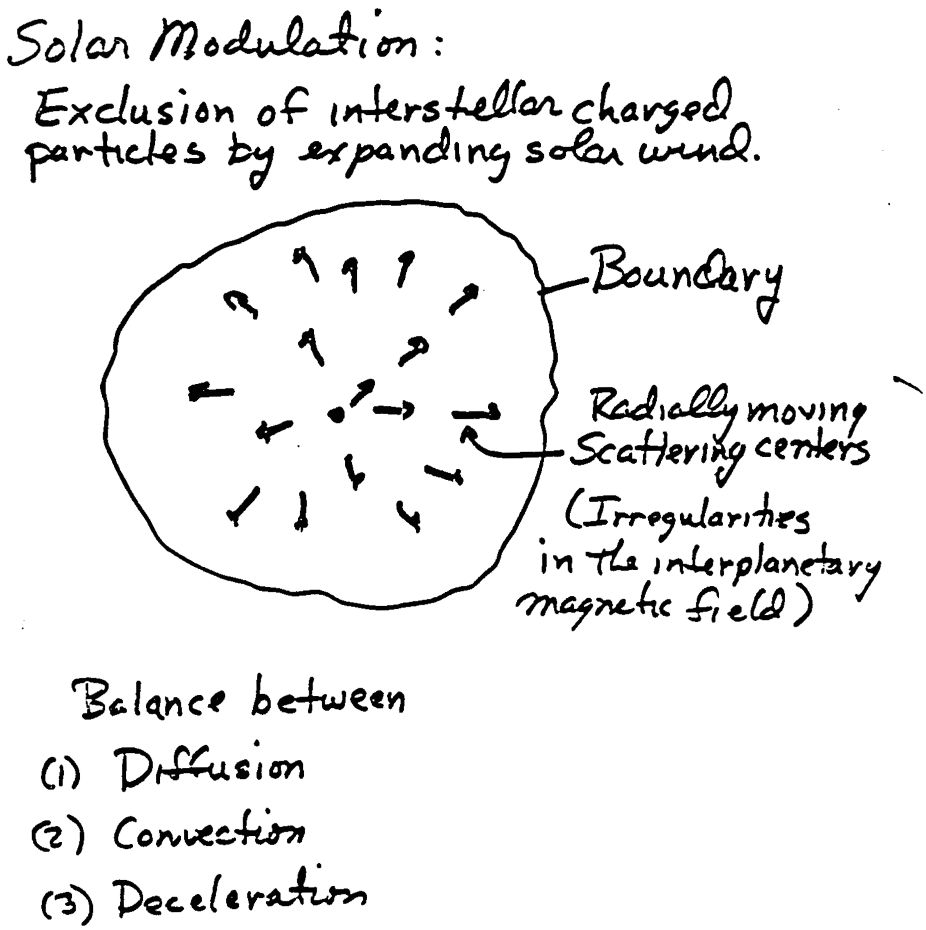
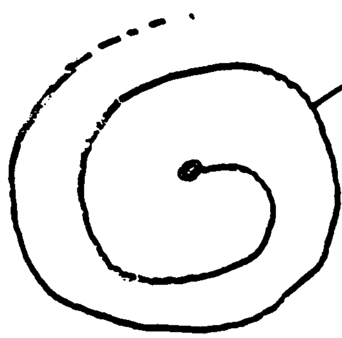



*Figure 2.* Schematic representation of solar modulation. Details are discussed in the text and references.

Origin of the Interplanetary Magnetic Field.



Locus of all solar wind originating from one point on the sun.

{Archimedes / Parker} spiral

**Because** (a) Solar wind is conductive.
(b) Solar surface is magnetized.

This locus is also a single magnetic field line

*Figure 3.* Interplanetary magnetic field has the same shape above and below the solar equator but opposite polarity as the dipole field is drawn out by the solar wind.

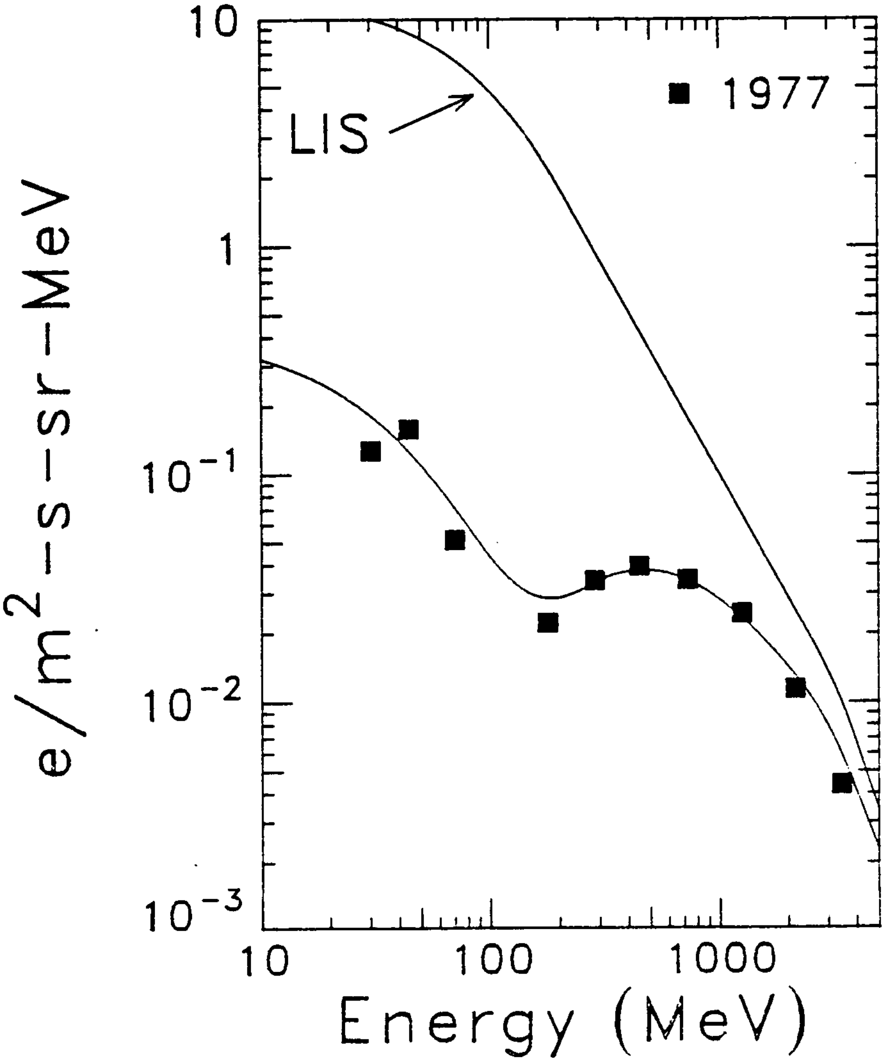



*Figure 4.* Comparing measured electron fluxes with the Local Interstellar Spectrum (LIS) deduced from radio data gives the only absolute measurement of the total amount of solar modulation. The 1977 electron spectrum shown is representative of maximum electron fluxes near Earth.

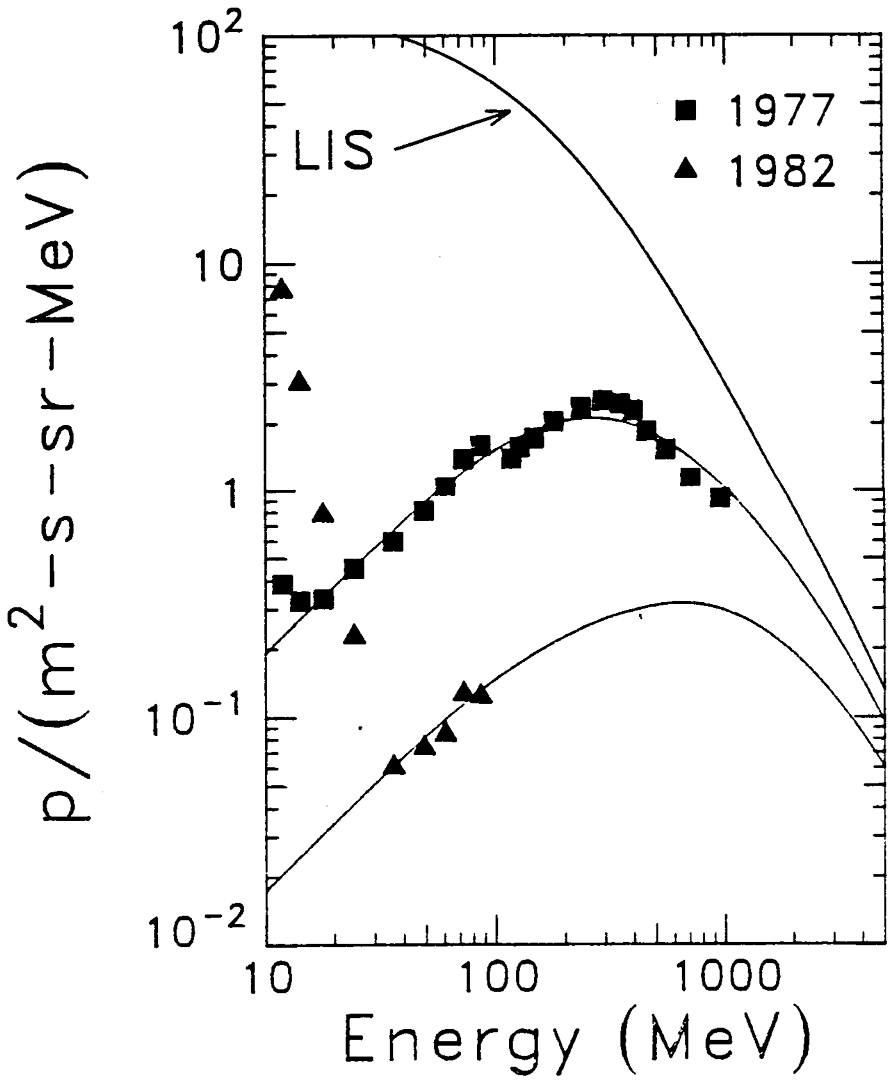



*Figure 5.* Comparison of maximum and minimum proton fluxes with model fits. The LIS for protons is an output of the model: the one shown here gives consistent results over the observed range of modulation.

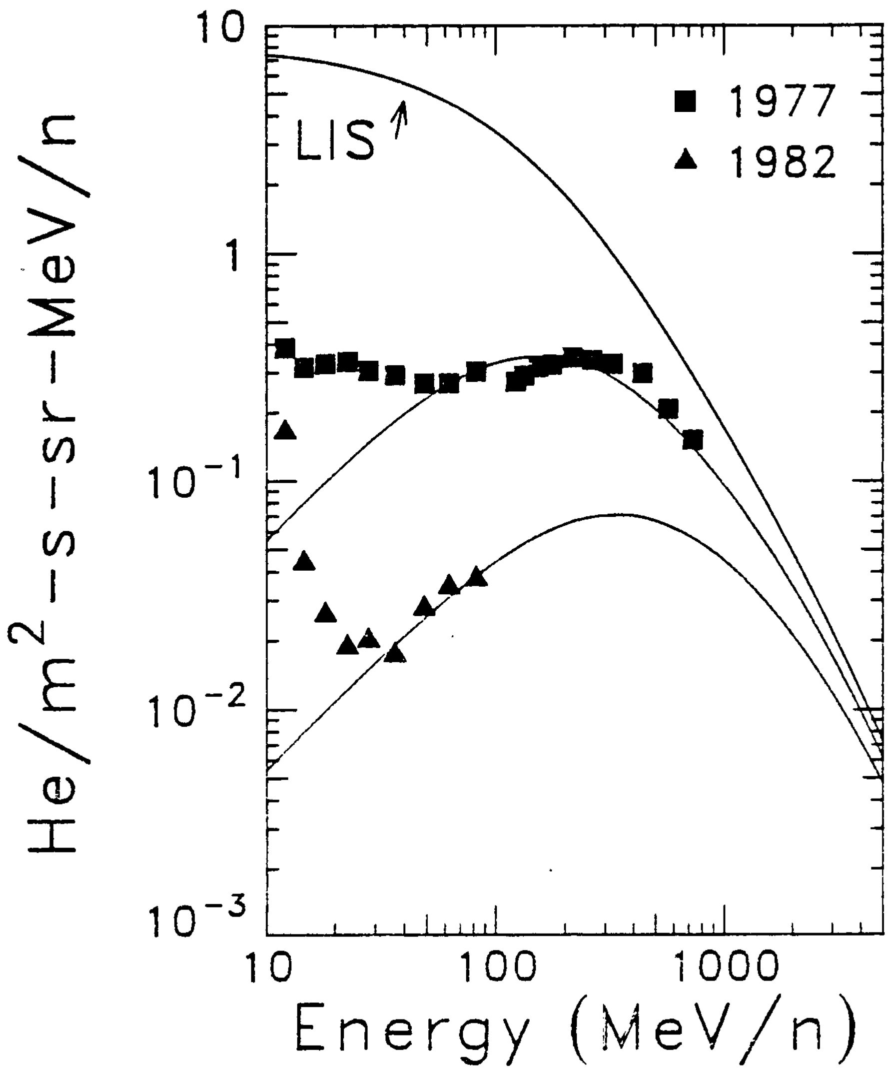



*Figure 6.* Helium data for comparison with the proton data in the previous figure. Subtle differences are discussed in the text.